Introduction
Provision of food has always been a challenge facing mankind. A major cornerstone in this challenge is the competition from insect pests. Particularly in the tropics and sub-tropics, where the climate provides a highly favourable environment for a wide range of insects, consequently massive efforts are required to suppress population densities of the different pests in post harvest phase in order to achieve an adequate supply of food. The introduction of alien pests into new habitats due to the global increase of trade and transport causes another dilemma. After the crop is harvested, it undergoes several operations that, if improperly done, may result in serious losses due to insect pest infestation (Laubscher and Cairns 1983, Giga 1987, Jonsson and Kashweka 1987, Gwinner et al. 1996). Insect pests inflict their damage on stored products/food commodities mainly by direct feeding. Thus, due to damage done by insects, food commodities lose value for marketing and consumption.

Food plants of the world are damaged by more than 10,000 species of insects, 30,000 species of weeds, 100,000 diseases (caused by fungi, viruses, bacteria and other microorganisms) and 1000 species of nematodes (Hall, 1995; Dhaliwal et al., 2007). However, less than 10 per cent of the total identified pest species are generally considered as major pests. The severity of pest problems has been changing with the developments in agricultural technology and modifications of farming practices (Dhaliwal et al. 2010). Despite the great investment for the application of millions of metric tonnes of pesticides, plus the use of various biological and other non-chemical controls worldwide, global crop losses remain a matter of concern (Pimentel, 2007, 2009).

World trade in agricultural commodities continues to grow. As agricultural trade expands, it increases the risk of introducing exotic insects into new areas where they may become plant pests. The establishment of new pests can be costly owing to increased crop damage, control programs, and quarantine restrictions on trade. Annual damages caused by exotic insects and mites have been estimated billions of US $ (Pimentel et al. 2002).

A quarantine pest is a plant pest of potential economic importance to an area that is not yet present there or that is present but not widely distributed and officially
controlled. Unless accepted disinfection measures are available, quarantine pests can disrupt marketing of fresh agricultural products not only between countries but also between geographical areas within countries. Therefore, effective postharvest quarantine treatments or pre or postharvest quarantine systems are essential to the unrestricted trade of fresh and durable commodities through domestic and international channels. Quarantine treatments or systems exclude, sterilize, or kill regulatory pests in exported commodities to prevent their introduction and establishment into new areas. Because exclusion is the goal when dealing with quarantine pests, the tolerance for viable pests in the commodity is essentially zero (Follett and Neven 2006).

A postharvest quarantine treatment may be required for a surface pest if infestations go undetected, such as when individuals are hidden inside fruit clusters (Armstrong 2001, Yokoyama et al 1990) or protected within various plant parts in the exported commodity (Whiting et al 1998).

The global phase-out in the use and production of methyl bromide, according to the Montreal Protocol (Anonymous 2000), has resulted in this treatment becoming more expensive, as well as increasing efforts to develop suitable alternative postharvest treatments (Fields and White 2002). Methyl bromide fumigation for quarantine purposes however, is exempt from the phase out plan until alternatives are available (Johnson and Neven 2010).

Quarantine or phytosanitary treatments such as heat, cold, irradiation, and fumigation disinfest host commodities of insect pests before they are exported to areas where the pests do not occur. In some cases, commodities are exported and receive treatment at the port of arrival. Whereas development of heat, cold, and fumigation treatments involves generating data for each commodity and pest combination, radiation treatments are developed for a pest species irrespective of the fruit or vegetable host. This is possible because ionizing radiation penetrates commodities quickly, so treatment time is short and the required dose can be applied without changing the commodity’s temperature, and most commodities can tolerate irradiation at levels that control the pests (Morris and Jessup 1994, Thomas 2001, Wall 2008).

Ionizing radiation breaks chemical bonds within DNA and other molecules, thereby disrupting normal cellular function in the infesting insect (Ducoff 1972, Koval 1994). Many tissues and functions of the insect may be disrupted by exposure to radiation (Vinson et al. 1969, Nation and Burditt 1994). Insects and other living organisms are able to repair molecular damage done by small amounts of ionizing energy (Alpen 1998), but large amounts are fatal or cause permanent sterility, and this is the basis for using irradiation to control insects in commodities.

Radiotolerance can vary among the life stages of an insect, and between insect taxa. For example, Lepidoptera tend to be more radiotolerant than Diptera, Coleoptera, and Hemiptera, although there is considerable variation among the species that have been tested within these groups (Bakri et al. 2005). For individual species, radiotolerance normally increases with increasing developmental stage when the goal is to prevent successful reproduction (e.g., Follett 2008). Unlike other disinfection techniques, irradiation does not need to kill the pest immediately to provide quarantine security, and therefore live (but sterile or not viable) insects may occur with the exported commodity.

The goal of a quarantine treatment is to prevent reproduction; therefore, the required response for a radiation treatment may be prevention of adult emergence (Follett and Armstrong 2004), induction of adult sterility (Follett 2006a), or $F_1$ sterility (Follett 2006b,c).

Phytosanitary irradiation (PI) is being used increasingly to disinfect fresh commodities of quarantine pests (Hallman 2011). One of the advantages of the technology compared with other treatments is that it has been very amenable to generic doses (one dose serves for a group of pests and commodities although not all
have been tested for efficacy) that facilitate treatment development and application (Hallman 2012).

A generic treatment is a single treatment that controls a broad group of pests without adversely affecting the quality of a wide range of commodities. Before generic treatments can be recommended, information is needed on effective irradiation doses for a wide range of insects within the taxon. Currently, two broad generic treatments (150Gy for all Tephritidae and 400Gy for all Insecta except pupal and adult Lepidoptera) are approved for use on imports to the United States and the 150Gy dose for Tephritidae is accepted by the International Plant Protection Convention (IPPC). The Joint Food and Agricultural Organization/International Atomic Energy Agency Programme of Nuclear Techniques in Food and Agriculture (FAO/IAEA) has been instrumental in the development of PI and generic doses and currently has a 5-yr 12 nation Cooperative Research Program (CRP) develop more generic treatment doses (IAEA 2009). In 2012, the IPPC issued a call for proposals for additional PI treatments including generic treatments for their treatment manual (IPPC 2011a,b). The proposed phytosanitary irradiation treatments undergo an evaluation process (Hallman et al. 2010).

Besides Diptera (tephritid fly) and lepidopteran (moths and butterflies) insects, mealybugs (Hemiptera: Pseudococcidae) also harbour economically important post-harvest insect pests (Sallam, 1997). The name "mealybug" is derived from the mealy or waxy secretions that cover the bodies of these insects. These are soft bodied and small sap-sucking insects and attack crops both in the field and in store. Some pest species of this group cause severe economic damage to a wide range of vegetable, horticultural and field crops in India. It is extremely difficult to control these mealy bugs because they are exotic pests and have a waxy skin, which provides them an effective protection.

Considering the sudden emergence of mealybug as a major pest of cotton across all cotton growing states of India and Pakistan, several questions are being raised to elucidate the reasons for pestilence. Information is clearly lacking on the composition of mealybug species that occur on cotton in various parts of India and on the
predominant species that causes economic damage across the country. There is a great concern in India that an exotic species has been introduced accidentally and that it may create havoc, not only on cotton, but on other crops as well, thereby threatening sustainable agricultural production in the country (Nagrare et al 2009).

Lower (1968) called the mealybug as “hard to kill pest of fruit trees”. Perhaps the most important factor is the habitat of the mealybug. Mealybugs live in protected areas such as cracks and crevices of bark, at the base of leaf petioles, on the underside of the leaves and also inside the grape bunches. Eggs of the mealybugs, protected by waxy filaments, are almost impossible to be penetrated with insecticidal sprays. Late instar nymphs and adult female mealy bugs are not affected by foliar application of insecticides since they are covered with waxy coating (McKenzie, 1967). Therefore, mealybugs pose a quarantine concerns in terms of post-harvest insect pest in agricultural commodity.

Various species of mealybugs have started appearing in serious proportions on field crops, vegetables, fruits and ornamentals (Tanwar et al., 2007). In fact, mealybugs have become indicator insects for the current ecosystem alterations due to slow changes in climate during the period from 2002 to 2005. Among these, *Phenacoccus solenopsis* Tinsley on cotton and *Paracoccus marginatus* Williams and Granara de Willink on papaya have become quite serious. The papaya mealybug, *P. marginatus*, has become quite alarming in Tamil Nadu, challenging the pesticides or other IPM measures. *Maconellicoccus hirsutus* (Green) causes extensive damage to ornamentals, though its host range extends to 76 families and over 200 genera, including beans, *Chrysanthemum*, citrus, coconut, coffee, cotton, *croton*, cucumber, grape, groundnut, guava, *Hibiscus*, maize, mulberry, pumpkin and rose (Tanwar et al., 2007; Rajendran, 2009).

Worldwide established pest status of mealybug species has acquired importance of quarantine concern, which needs to focus on effective phyto-sanitary treatment to control mealybug infestation and maintain the quality of food commodities at trade level. Among various internationally established mealybug species of quarantine importance (Culik and Gullan 2005), the Solenopsis mealybug, *Phenacoccus*
solenopsis, the Pink hibiscus mealybug, *Maconellicoccus hirsutus* and the Papaya mealy bug, *Paracoccus marginatus* have gained status of serious quarantine pests that would poses a threat to many agricultural and ornamental plants in India.

The Solenopsis mealybug, *Phenacoccus solenopsis* Tinsley has been known exotic pest to India, and has caused widespread infestation on cotton and crops of 14 families in India (Nagrare et al. 2009), with present status as and became a major pest of cotton across all cotton growing states of India. The Pink hibiscus mealybug, *Maconellicoccus hirsutus* is a serious and invasive pest of cotton and *Hibiscus rosasinensis* in India (Hodgson et al 2008) and this pest has been found on 215 genera of plants (Hakim et al. 2012). The pink hibiscus mealybug, *Maconellicoccus hirsutus* (Green), is a USDA, APHIS quarantine pest because of its wide host range and high rate of infestation in many regulatory export and import commodities (Jacobson and Hara 2003). The papaya mealy bug, *Paracoccus marginatus* (Williams & Granara de Willink) has invaded India recently and the first record was evidenced from Coimbatore, Tamilnadu in July 2008 on papaya and assumed the status of a major pest in 2009 in India (Mahalingam et al. 2010). The mealybug *Paracoccus marginatus* recently has gained status of new quarantine surface pest and so the commercial treatment dose was increased to 400Gy to prevent rejections of agricultural commodity at quarantine inspection port. Therefore, Irradiation studies are needed with *P. marginatus* before generic dose levels can be lowered again from 400Gy (Follett 2009).

Generic doses can be lowered after developing specific dose for concerned pest species (Follett 2009, Hallman et al 2010). Combination treatment with temperature can be used to lower the generic doses (Hallman 1998, Benschoter 1983, Follett 2009). Few and inconclusive studies addressed the effect of temperature on efficacy of phytosanitary radiation when it was reviewed by Hallman (2000). more studies are warranted before a definite conclusion should be made.

Many quarantine treatments of agricultural commodities are directed against these mealybug pests, and a considerable effort in detection and population control is being expended in our country to prevent these pest species from invading new territories.
Among various quarantine treatments, phytosanitary irradiation is recognized as a versatile treatment with broad spectrum activity against arthropod pests at dose levels that have minimal adverse effects on the quality of most commodities.

The present study was undertaken to assess the bioefficacy of gamma radiation as phytosanitary treatment against the various ontogenetic stages of Phenacoccus solenopsis, Maconellicoccus hirsutus and Paracoccus marginatus in order to ascertain the disinfestation gamma dose range (phytosanitary irradiation) for each species, and henceforth to identify the generic dose for species complex of mealybugs.

The present work was attempted with following objectives,

(i) Study bio-efficacy of gamma radiation on pre-imaginal stages of mealybug species, Phenacoccus solenopsis, Maconellicoccus hirsutus & Paracoccus marginatus

(ii) Determine the effective doses for 50%, 90% & 99.9% response (i.e. ED$_{50}$, ED$_{90}$ & ED$_{99.9}$) of gamma radiation for phytosanitary irradiation of pre-imaginal stages of mealybug species, with respect to metamorphic inhibition, check in adult formation, and sterility

(iii) Study bio-efficacy of gamma radiation on imaginal stages of mealybug species, Phenacoccus solenopsis, Maconellicoccus hirsutus & Paracoccus marginatus

(iv) Determine the effective doses for 50%, 90% & 99.9% response (i.e. ED$_{50}$, ED$_{90}$ and ED$_{99.9}$) of gamma radiation for phytosanitary irradiation of imaginal stages of mealybug species with respect to parental sterility, and F$_1$ sterility.

(v) Determine the influence of temperature on radiation bioefficacy against mealybug species, Phenacoccus solenopsis, Maconellicoccus hirsutus & Paracoccus marginatus

The aforesaid objectives were studied in order to identify most radioresistant pre-imaginal and imaginal stage and establish phytosanitary irradiation for each species and determine an overall generic gamma dose for this group of mealybug species.